HEAVY VECTOR LEPTONS AT THE SSC

V. Barger,[1] N. G. Deshpande,[2] W.-Y. Keung,[3]
M. H. Reno[4] and M. Ruiz-Altaba[5]

[1]Physics Dept., Univ. of Wisconsin, Madison, WI 53706.
[2]Physics Dept., Univ. of Oregon, Eugene, OR 97403.
[3]Physics Dept., Univ. of Illinois, Chicago, IL 60680.
[4]Fermi Nat. Accelerator Laboratory, Batavia, IL 60510.
[5]Physics Dept., Univ. of Florida, Gainesville, FL 32611

SUMMARY

We describe the production and decay of heavy lepton doublets with vector couplings to W's and Z's. With production cross sections enhanced relative to sequential leptons, the mass degenerate charged and neutral vector leptons are copiously pair-produced at the SSC for masses below a few TeV. They decay with striking signatures: $e\bar{e}WZ$, $e\bar{e}WW$ and $e\bar{e}ZZ$.

INTRODUCTION

Grand unified[1] and superstring-inspired[2] models introduce more fermions into each of the presently known three generations of quarks and leptons. We focus here on models with additional leptons, notably those appearing in the 27-dimensional representation of E_6[3].

The colorless fields in the fundamental representation (27) of E_6 contain the usual lepton doublet $(\nu,e)_L$ as well as two additional left-handed doublets of Weyl fermions: $L=(\nu_E,E)$ and $\bar{L}=(E^c,\ \nu_E^c)$ with opposite hypercharges. The left-handed anti- particles can be thought of as the "right-handed components" of the Dirac spinor. Since both left and right components belong to doublets of $SU(2)_W$, they will couple vectorially to W's and Z's.

In most analyses[4] of E_6, one assigns to these new doublets zero lepton and baryon number, whereby their scalar components have positive R-parity and can be readily identified with the standard electroweak higgs fields. We choose instead to assign to these vector doublets a unit lepton number (and zero baryon number) so the even-R component is the fermionic one which can mix only with the usual leptons without violating any global symmetries.

If the vector leptons are light enough to be seen at the SSC, an additional symmetry is required in the theory to protect L from pairing up with $\bar{L}$ at a high scale. Such a symmetry does arise naturally in superstring inspired models. Once the symmetry is broken, a mass term of the form above gives a <u>common</u> mass M_L to ν_E and E.

We describe the mixing of ordinary leptons with vector leptons, and its consequences for ν_E and E decays. We treat the case of a single generation to avoid the encumbrance of a flavor mixing matrices, inessential for the general idea. Keep in mind throughout that "electron" stands for any charged ordinary lepton, namely either e, μ or τ. Then, we exhibit the expected production cross sections and some interesting distributions of the decay products in Figures 1-4.

MASS MATRICES AND MIXINGS

There are three types of mass terms for the leptons,[5,6] according to the amount of weak isospin violation inherent in them. $\Delta I_W=0$ mass terms can be very large. They include the $\nu_R\cdot\nu_R$ right-handed neutrino Majorana mass, the mixing term between the usual left-handed lepton doublet and the new right-handed doublet, and -most importantly- the central mass for the L and $\bar{L}$ lepton doublet pairing, which is the same Dirac mass for both ν_E and E. $\Delta I_W=1/2$ mass terms are the best known. They give Dirac masses to the electron and the neutrino, and couple the right-handed singlets to the new doublets under scrutiny. Finally, two doublets can couple vector-like into a $\Delta I_W=1$ mass term, thus generating a Majorana mass for the left-handed neutrino and also the mass splitting between the ν_E and E fields. $\Delta I_W=1$ masses must be tiny, so that the heavy leptons ν_E and E are, for all experimental purposes, <u>degenerate in mass</u>. They would be stable particles were they not mixed with the usual leptons.

All the lepton masses must arise from Yukawa couplings to scalars which get vacuum expectation values (vev's). Rewriting the combinations of Yukawa couplings and vev's as masses, the most general (Dirac) mass matrices for a single generation of charged and neutral leptons are

$$\mathcal{M}^+ = \begin{array}{cc} \begin{bmatrix} m_1 & M_1 \\ m_2 & M_2 \end{bmatrix} & \begin{array}{c} e \\ E \end{array} \\ \begin{array}{cc} e^c & E^c \end{array} & \end{array}$$

$$\mathcal{M}^0 = \begin{array}{cc} \begin{bmatrix} m_3 & M_1 \\ m_4 & M_2 \end{bmatrix} & \begin{array}{c} \nu \\ \nu_E \end{array} \\ \begin{array}{cc} \nu^c & \nu_E^c \end{array} & \end{array}$$

The $\Delta I=0$ masses are denoted by M_i, and the $\Delta I = 1/2$ masses, by m_i. We have assumed that the $\Delta I=0$ vev's break a new (as yet, undiscovered) symmetry, so we take $m_i^2 \ll M_j^2$ in our subsequent analysis.

For the ordinary left-handed neutrino to end up ultralight as it is, ν^c must be effectively decoupled, either because it has a large Majorana mass or because its Yukawa couplings to ν and ν_E are symmetry-suppressed. In either case, this is reflected by setting $m_3 = m_4 = 0$.

The matrices $\mathcal{M}^+$ and $\mathcal{M}^0$ are rotated to diagonal form to find the mass eigenstates. Even though the two-by-two matrices are straightforward to diagonalize, the features common to the more general case of several generations (when each of the entries above are 3x3 matrices) are most easily seen in a two-step diagonalization. The idea is to treat the $\Delta I=1/2$ masses as perturbations to the $\Delta I=0$ mass matrix. A large rotation ($\tan\theta = M_1/M_2$) diagonalizes the $\Delta I=0$ mass matrix, common to both charged and neutral leptons, leaving the (left-handed!) electro- weak gauge interactions invariant. If we ignore the $\Delta I = 1/2$ mass term, this single left-handed rotation diagonalizes both matrices $\mathcal{M}^+$and $\mathcal{M}^0$, giving a massless doublet and a massive one.

By assumption, the neutrino mass matrix is diagonal after this first rotation. Restoring m_1 and m_2 to the rotated charged lepton mass matrix, we obtain

$$\tilde{\mathcal{M}}^+ = \begin{bmatrix} \tilde{m}_1 & 0 \\ \tilde{m}_2 & M_L \end{bmatrix}$$

where

$$\tilde{m}_1 = \frac{m_1M_2-m_2M_1}{M_L}$$

$$\tilde{m}_2 = \frac{m_1M_1+m_2M_2}{M_L}$$

and

$$M_L = \sqrt{M_1^2 + M_2^2}$$

is the common $\Delta I=0$ mass of E and ν_E.

A simple trick to find the final left- and right-handed rotations needed to diagonalize $\tilde{\mathcal{M}}^+$, is to consider the symmetric matrices $\tilde{\mathcal{M}}^+\tilde{\mathcal{M}}^{+T}$ and $\tilde{\mathcal{M}}^{+T}\tilde{\mathcal{M}}^+$. The former is diagonalized by a left-handed rotation matrix with angle $\theta_L \sim \frac{\tilde{m}_1\tilde{m}_2}{M_L^2} = \eta_L^2$, and the latter, by the right-handed rotation $\theta_R \sim \frac{\tilde{m}_2}{M_L} = \eta_R$ where the parameters η are of magnitude m/M, the ratio of $\Delta I_W=1/2$ to $\Delta I_W=0$ masses.

Right-handed currents provide vector leptons with their main decay channels.[6] Flavor changing neutral currents for the usual fermions will be suppressed because θ_L is small, which makes it unlikely that new heavy vector leptons could be inferred from low energy data.

SIGNATURES AT THE SSC

The flavor violating terms of the interaction lagrangian are

$$\mathcal{L} = \frac{g}{\sqrt{2}} W^\mu[\bar{\nu}_{eL}\gamma_\mu(e_L + \theta_L E_L) + \bar{\nu}_{EL}\gamma_\mu(E_L - \theta_L e_L)$$

$$+ \bar{\nu}_{ER}\gamma_\mu(E_R - \theta_R e_R)] - \frac{g}{2\cos\theta_W} Z^\mu(\bar{e}_R\gamma_\mu\theta_R E_R) + \text{h.c.}$$

We could also add terms involving extra gauge bosons like

$$g \tan\theta_W Z'_\mu \bar{e}_R\gamma^\mu\theta_R E_R$$

It follows that ($x_W = \sin^2\theta_W$) the decay widths are:

$$\Gamma(\nu_E \to eW) \sim \theta_R^2 \frac{3\alpha M_L}{16x_W}(1 - \frac{M_W^2}{M_L^2})^2$$

$$\Gamma(E \to eZ) \sim \theta_R^2 \frac{3\alpha M_L}{32x_W(1-x_W)}(1 - \frac{M_Z^2}{M_L^2})^2$$

$$\Gamma(E \to \nu_e W) \sim \theta_L^2 \frac{3\alpha M_L}{16x_W}(1 - \frac{M_W^2}{M_L^2})^2 \sim \theta_R^2\,\Gamma(E \to eZ).$$

The vector neutrino ν_E has only charged current decays but the charged vector lepton E decays mostly through neutral current couplings.

Crucially, for either E or ν_E, the heavy lepton's branching ratio into a light charged lepton plus a weak gauge boson is very close to unity, thus allowing for very easy triggering. Except for the neutrino decay modes of the gauge bosons, final states can be used to fully reconstruct the vector lepton masses, and thus clearly distinguish vector leptons from sequential ones. The events where the Z decays into a charged lepton pair should be particularly easy to detect. <u>One would expect events with as many as six muons in the final state</u>, three of which would reconstruct to the same invariant mass as the other three. Good W and Z identification in jet modes would, however, seem to be an obvious requirement (for this kind of physics) on the detectors to be installed at the SSC.

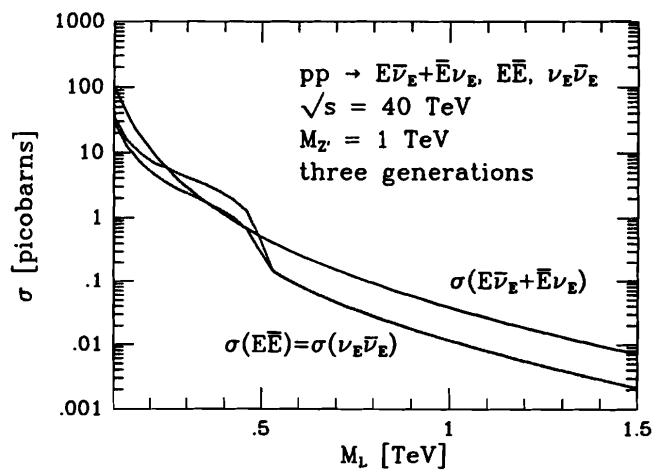

FIGURE 1. The total cross-section in picobarns as a function of M_L for pp → E $\bar{\nu}_E$ + $\bar{E}\nu_E$ is indicated by the solid curve. The cross-sections for pp → $E\bar{E}$ and pp → $\nu_E\bar{\nu}_E$ are approximately equal. The higher (lower) dashed curve represents $\sigma(E\bar{E})$ where the E_6-predicted minimal extra U(1) gauge boson Z' accounts for the bump with $\Gamma_{Z'}$=10 GeV ($\Gamma_{Z'}$=20 GeV) and $M_{Z'}$=1 TeV.

To exhibit the mass range to which the SSC is sensitive, Figure 1 shows the total Drell-Yan cross-sections for $E\bar{E}$, $\nu_E\bar{\nu}_E$, and $\bar{E}\nu_E + E\bar{\nu}_E$. Three families of vector leptons are included, degenerate in mass. We used a K-factor of $(1 + \frac{8\alpha_s \hat{s}}{\pi})$ and Set 1 of the Duke and Owens structure functions[7] in this calculation. The only unknown parameter in the cross-section is M_L. With $\sqrt{s}$ = 40 TeV and an annual integrated luminosity of 10^4 pb^{-1}, the cross-section will be readily observable for $M_L \lesssim 1$ TeV. The charged current process is independent of the mass of a hypothetical extra neutral gauge boson Z', so we focus our attention on it here.

The results in Figures 2, 3 and 4 were generated using the matrix element[8] for $q_1 \bar{q}_2 \to W^- \to E\,\nu_E \to e\bar{e}$ W^-Z^0 with the same structure function weights and K-factor as in Figure 1, and with a fixed vector lepton mass M_L of 500 GeV.

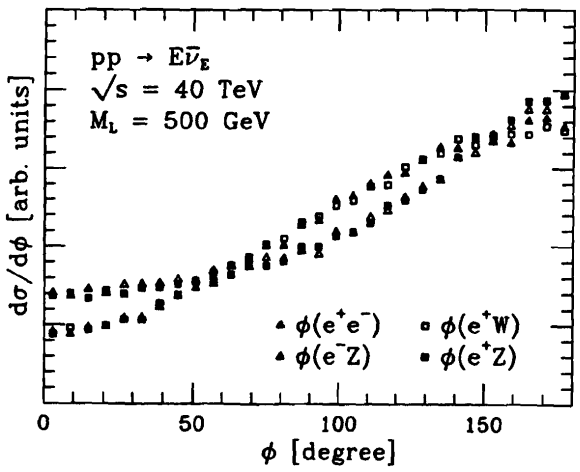

FIGURE 2. Relative azimuthal angular distributions of the four particles in the final state from $pp \to E\bar{E}$. It is primarily kinematics that govern $d\sigma/d\phi$ so all the ϕ distributions are similar, generally providing experimenters with good angular separation between the charged leptons and/or the gauge bosons.

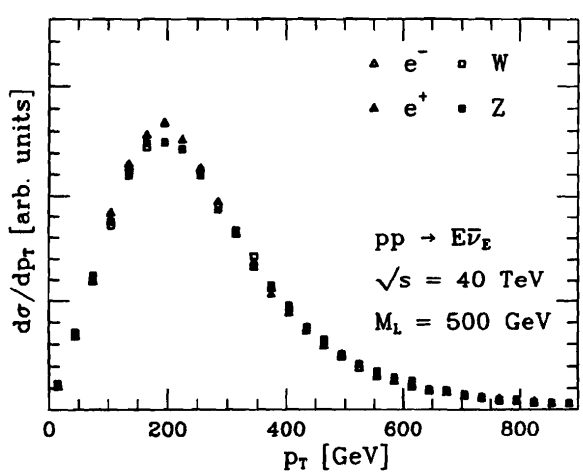

FIGURE 3. Transverse momentum distributions of the four particles in the final state from $pp \to E\bar{\nu}_E$. The peak is just below a $p_\perp$ of half the mass of the vector lepton.

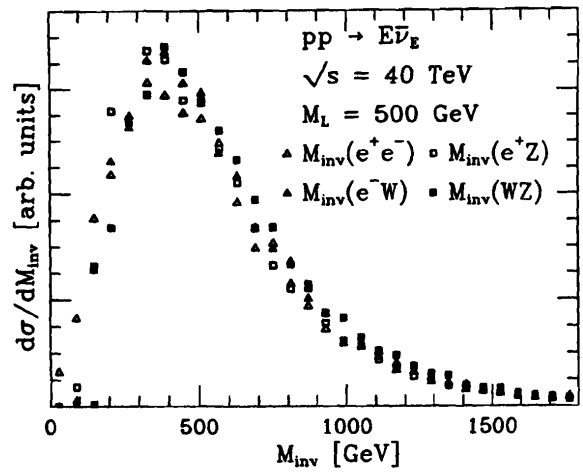

FIGURE 4. Invariant mass distributions for pairs of particles from $pp \to E\bar{\nu}_E$.

We have shown that vector leptons, if they exist below about a TeV, will produce clear leptonic signals at the SSC. The fully reconstructable heavy lepton decays with no missing energy, together with the enhanced cross-section and high-p_T electron and positron will allow to distinguish these particles from sequential leptons and standard model backgrounds. Our results generalize to mixing schemes involving all three generations of light leptons by including also muons and taus in the final state. We finally emphasize that while we have considered these new particles in the context of superstring inspired models, our analysis is more generally applicable and probes the mechanisms for mass generation in the standard model.

ACKNOWLEDGEMENTS

This work was begun at the 1986 Snowmass Workshop. M. H. Reno thanks F. del Aguila for emphasizing the phenomenological consequences of ref. 6. M. Ruiz-Altaba thanks P. Ramond for useful conversations. W.-Y. Keung thanks Fermilab for use of research facilities. This research was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the U. S. Department of Energy under contracts DE-AC02-76ER00881, DE-FG02-84ER40173, DE-AS05-81ER40008, and DE-FG06-85ER40224. Fermilab is operated by Universities Research Association, Inc. under contract with the U. S. Department of Energy.

REFERENCES

1. See, for instance, G. G. Ross, "Grand Unified Theories", Benjamin Cummings, New York (1985).
2. E. Witten, Nucl. Phys. B258 (1985) 75; M. Dine et al., Nucl. Phys. B259 (1985) 549.
3. F. Gursey, P. Ramond and P. Sikivie, Phys.Lett. 60B (1976) 177.
4 For instance, V. Barger, N. G. Deshpande and R. J. N. Phillips, K. Whisnant, Phys. Rev. D33 (1986) 1912.
5. P. Ramond, in Proceedings of the 1981 INS symposium on Quark and Lepton Physics (Tokyo,1981), eds. K. Fujikawa, H. Terazawa and A. Ukawa (University of Tokyo Press, 1981); P. Fishbane, S. Meshkov and P. Ramond, Phys. Lett. 134B (1984) 81.
6. F. del Aguila and M. J. Bowick, Phys. Lett. 119B (1982) 144, and Nucl. Phys. B224 (1983) 107.
7. D. Duke and J. S. Owens, Phys. Rev. D30 (1984) 49.
8. With different coupling constants, the matrix element appears in H. Baer, V. Barger and R. J. N. Phillips, Phys. Rev.D32 (1985) 668.